A PARAMETRIC STUDY OF RAREFIED JET INTERACTION USING DSMC

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A parametric study free jet plume interactions in the transitional regime is conducted. Results show that similarity in the resulting secondary jet based on conditions of the primary jets can be found only for mass and momentum transfer. However, such similarity does not appear to hold for energy transfer. This fact provides the basis for establishing an analytic model for the plume interaction flowfield at high altitude suitable only for the impingement force predictions. The separation distance is a proper length scale in studying the plume interaction in the Knudsen number range simulated. The linear superposition method is also shown not to be accurate except in free molecular plume interaction.

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1 Introduction

A renewed interest in studying the interactions of plumes expanding in a vacuum is prompted by the challenge of the Space Station design. An essential part of the station design task is to accurately predict the loads and contamination on the solar array (and other sensitive surfaces) from the Orbiter reaction control system (RCS) plume impingement during proximity operations. Since the complex maneuvering of the proximity operation in the vicinity of the station demands a myriad of cases of the RCS engine firings, the prediction of the RCS plume impingement is a formidable problem. The difficulty of the prediction is exacerbated in the case of multiple RCS engine firings because of the multiple plume interaction.

The Orbiter RCS consists of 44 engines, of which 38 are the primary engines of 870 lbf nominal thrust and the rest are vernier engines of 25 lbf thrust. The locations of the RCS engines on the Orbiter are separated by distances ranging from less than a meter to more than 30 meters. Any combination of the engines to be fired are possible in the maneuvering, of course, those symmetrical with respect to the Orbiter axes are most likely to be used. Considering the thrust level and the range of the spacing, it is obvious that the attempts to resolve this problem either by experimental or by numerical simulation are very challenging. Therefore, the analysis of the impingement problem related to multiple RCS plumes is a major source of the uncertainty in the space station design.

In previous work [1, 2], efforts have been made to tackle the problem by using a direct simulation Monte Carlo code to compute representative cases of the RCS multiple engine firings. The results have indicated that the current model for predicting the multiple plume flow field as a linear superposition of each single plume from the RCS engines is highly inaccurate for practically all the RCS nozzle separation distances on the Orbiter[1]. The code used for the RCS simulation has been validated by the successful simulation [2] of a well documented experiment in which free jet interactions were systematically investigated in a vacuum chamber[6]. The computed flow field of the free jet interaction has been compared against the experiment data and shows remarkably good agreement. Thus, the DSMC approach may be used for the subject study with confidence.

For the space station engineering design, however, those accomplishments are still short of supplying a reliable model for predicting the flow field resultant from the multiple RCS engine firings. In engineering practice, high altitude plume flow field predictions are usually expressed by an analytical formula. For a single plume, frequently the source flow model is assumed and the density field can be expressed as a function of downstream distance and off-center angle in a closed form. This approach has been proved to be effective and adequately accurate for engineering design purposes [9, 15, 16, 17, 18, 19]. Even in today's advanced computing environment the approach is still attractive because a huge number of cases typically need to be evaluated in a real time. In a shuttle proximity operation around the space station the RCS plume loads on the solar array must be predicted before the next maneuvering is decided.

The present work is the first step toward establishing an analytical model for the prediction of the flow field resultant from multiple plume interaction at high altitude. In the past, a few investigators have made contributions revealing the complex nature of the plume/free jet interaction, such as [4, 5, 6, 7]. Koppenwallner has introduced a scaling parameter, the penetration Knudsen number Kn_p , to classify the flow regime in which the interactions of two plumes takes place [4]. Later studies [5, 6, 7] reported certain trends of the flow field resulting from interacting free jets in a vacuum chamber. Due to the complexity of the flow nature and the difficulty in conducting experiments at low densities, no analytical model has been suggested so far for a multiple plume flow field, as the counterpart of the single plume model.

With the capabilities developed in [2], a parametric study is conducted in the present work, using the DSMC simulation on the flow field produced by two interacting free jets expanding into vacuum. There have been many studies investigating DSMC nozzle flows and their extending plumes for the single nozzle case (see for example [11, 12, 13, 14]). The current work examines multiple plume flow fields in a general three-dimensional framework using the DSMC method. Particulary, effort is focused on the interaction in the transitional regime. Since majority of plume interactions taking place in the space environment are fallen in this regime due to either small engines such as satellite attitude control thruster, or large separation distances between firing engines such as the RCS on the Orbiter. And also, because of the difficulties encountered in measuring and visualizing the highly rarefied flow resulted from the transitional plume interaction, less investigation has been conducted in this regime comparing to the continuum regime and free molecular regime which has better understanding analytically. Thus the present study is to obtain the characteristics of the flow field of the transitional plume interaction by taking advantage of newly developed massive parallel supercomputing technology.

2 Computational Method

The present work uses data parallel algorithms which are described in [1, 2, 3]. The computer code itself is basically the same as the one employed in [2]. With the current capabilities, such as the dynamic array resizing and the adaptive grid grouping, the code has been proved efficient and robust as a powerful tool to study this particular problem.

3 Approach

In earlier work by Dankert *al* [5], it was shown that for $Kn_{p_{min}} < 0.02$indicates interaction with continuum flow feature (shocks), while for $Kn_{p_{min}} > 2$ a mutual free molecular penetration of two plumes is possible. The interaction shock starts broadening when $Kn_{p_{min}} > 0.02$, and are merged into a shock layer when $Kn_{p_{min}} > 0.2$. The present study investigates the rarefied end of the transitional regime of plume interaction, i.e., for $0.2 < Kn_{p_{min}} < 2$. The variation of $Kn_{p_{min}}$ is obtained by changing the separation distance between two parallel free jets expanding into vacuum and keeping the exit Knudsen number, Kn_0, fixed at 0.03. The exit Knudsen number here is defined as $Kn_0 = \lambda_0/d$, where λ_0 is the mean free path at the orifice exit and d is the diameter of the orifice. The separation distance is varied from $L/d = 1.5$ to $L/d = 6.0$, where L is the distance between centers of the two orifices. Therefore, using the definition of $Kn_{p_{min}}$ given by[4], $Kn_{p_{min}}$ in the present simulation ranges from $0.33 - 1.32$. The simulated gas is molecular nitrogen.

The simulation employed a cartesian grid of cells of dimensions $50 \times 110 \times 50$ for $L/d < 6$, and $60 \times 110 \times 60$ for $L/d = 6$. The orifice has a diameter of 10 cells and is oriented with its axis aligned in the y direction (see Fig. 1). Thus the plane xy goes through the jet center line and is perpendicular to the symmetry plane yz, which is specularly reflecting.

The computation was performed on the Connection Machine CM-5, a massively parallel supercomputer by Thinking Machines Corp., at the Numerical Aerodynamic Simulation (NAS) facility at NASA Ames Research Center. Each simulation required 4,500-5,000 steps to complete and employed between 3 million and 4.5 million particles. The adapted grids had from 45,000 to 53,000 cell groups, always less than a quarter of the original total cells. Each case took approximately 8 hours of CPU time on 64 nodes of the CM-5. The average particle update time through steady state was 1.9 μsec. Particle cloning was used during the transient to speed up convergence.

4 Results

The computation was carried out to 10 diameters downstream from the orifice exit plane. A total of four cases is simulated, namely, a single jet expansion and three dual jet interaction cases with separations of $L/d = 1.5, 3.0$, and 6.0. Due to the symmetric nature of the flow, the computational domain only covers half of the field. Mach number contours in the xy plane for the three calculations are presented in Figures 2 - 4. The basic flow feature is that the two primary jets originating from the orifices are disturbed by a secondary jet which results from their interaction. The existence of the secondary jet is reported in earlier experimental works[6, 7] and in simulations[2]. However, the characteristics of the secondary jet is not fully understood, especially in the transitional regime with high penetration Knudsen number.

A better understanding of the secondary jet is the key to building an analytical model for plume interaction. Because the primary jet flow can still be described by the conventional source flow model before the secondary jet disturbance takes place, this work is focused on the secondary jet. The presence of the secondary jet and its extent of disturbance into the primary jet as a function of the separation distance can best be depicted by Mach contours shown in Figures 2 to 4 for $L/d = 1.5, 3.0$, and 6. It is evident that the extent of disturbance increases as the separation increases. It is naturally an indication that the separation distance should be taken as a length scale for the given Kn_0 of the simulation, but the fundamental question is whether the secondary jet self-similar.

Like the primary jet, the secondary jet also has its maximum value of flow properties along its axis, i.e. $x = 0; z = 0$. The distributions of density, dynamic pressure and translational temperature along the secondary jet axis are plotted against downstream distance scaled by separation distances, namely y/L, and presented in Figures 5, 6, and 7. All quantities have been normalized by the orifice exit plane value. It is interesting to see that the curves for normalized density and dynamic pressure, when scaled by $(L/d)^2$, follow each other quite closely. The temperature results, especially for $L/d = 3.0$ and 6.0, also follow each other well but only when left unscaled. In all instances the results for $L/d = 1.5$ do not collapse as well as for $L/d = 3.0$ and 6.0. This is probably due to inaccuracy in that solution since the $L/d = 1.5$ case has the orifice boundary only 2.5 cells from the symmetry plane.

To examine the extent of the disturbance of the secondary jet on the primary counterpart a set of data were collected on the primary jet axis and compared with data from the single free jet as a reference. The degree of the disturbance can be observed by plotting the relative differences between quantities. In other words, for the quantity q we consider the ratio $(q-q_o)/q_o$ where q is the value in the presence of the secondary jet and q_o is the undisturbed value obtained from the single jet simulation. Figures 8, 9, and 10 show the relative differences for density, dynamic pressure and temperature. The curves for density and dynamic pressure again collapse to a single curve when plotted as a function of y/L. This implies that for density and dynamic pressure the influence of the secondary jet is fully correlated to the separation distance. The temperature data is more difficult to interpret. The temperature results collapse in part when plotted as a function of $y/\sqrt(L)$. For $y/\sqrt(L) < 5$ the curves follow quite closely, but thereafter they diverge dramatically. This seems to indicate that the influence of the secondary jet on temperature in the primary jet is nonlinear. The influence is felt earlier than with density and dynamic pressure, and the degree of the influence is not self-similar.

These results indicate that a similarity based on the location of the primary jets does exist for the secondary jet but only where mass and momentum transfer are concerned. Therefore, for density and dynamic pressure the separation distance can be taken as a length scale for a given Knudsen number. The failure of similarity in the temperature data is somewhat surprising. It seems to indicate that the secondary jet constitutes a thermodynamic system independent of the two primary jets. Further investigation will be required before a clear understanding of the thermodynamics of the secondary jet may emerge.

In addition to confirmation of similarity for density and dynamic pressure, this parametric study also reveals another important character of the secondary jet. Figure 11 shows the ratio of the dynamic pressure of the secondary jet along its own axis and that of the undisturbed single jet along an axis displaced a distance L from its center. The results are shown plotted against the scaled downstream distance y/L. It is interesting to note that the three curves asymptotically approach three different values. For $L/d = 1.5$ the curve reaches a value slightly under 2.5; for $L/d = 3.0$ the value is about 2.3; and for $L/d = 6.0$ the curve seems dwelling around the value 2.0, although the simulation did not extend far enough to show exactly what value. This result has a significant engineering implication. It shows that predicting the multiple plume flowfield as a linear superposition of each single plume is highly inaccurate, even for the transitional interaction. Only in the case of $L/d = 6.0$, which has a minimum penetration Knudsen number of 1.32, does scalar linear superposition provide an adequate approximation. It also confirms that $Kn_{p_{min}} > 2.0$ is a good approximation for the start of the free molecular plume interaction regime.

5 Conclusions

The present parametric study on the free jet plume interactions in the transitional regime has shown that similarity in the resulting secondary jet based on primary jets can be found only for mass and momentum transfer. This fact provides the basis for establishing an analytic model for the plume interaction flowfield at high altitude. However, such a model probably will be accurate only for the impingement force predictions due to the non-linearity of thermodynamics of the secondary jets. The separation distance is shown to be a proper length scale in studying the plume interaction in the Knudsen number range simulated. Finally, the linear superposition method is fount not to be accurate except in free molecular plume interaction.

Further investigation is needed to establish a model for predicting multiple plume flowfields. The simulation needs to be extended further downstream and the range of the penetration Knudsen number needs to be expanded. Finally, the thermodynamics of the secondary jet needs further investigation before a full understanding of the multiple plume flowfield can be achieved.

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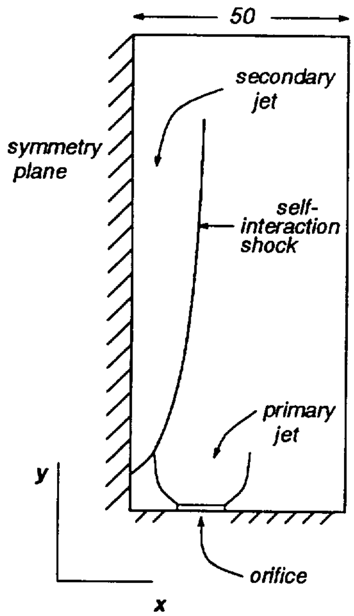

Figure 1: Geometry for DSMC simulation.

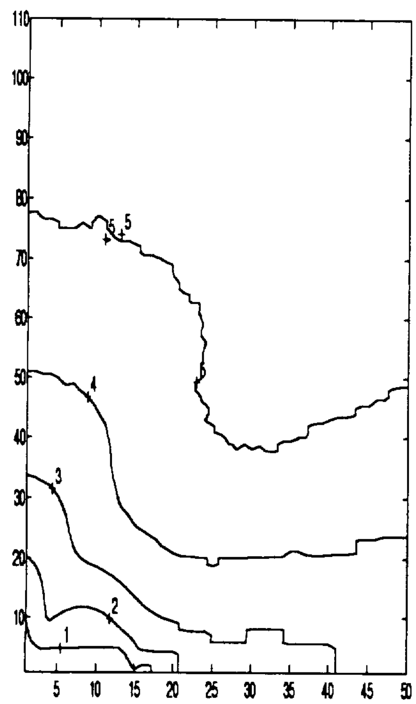

Figure 2: Mach contours in xy plane for $L/d = 1.5$

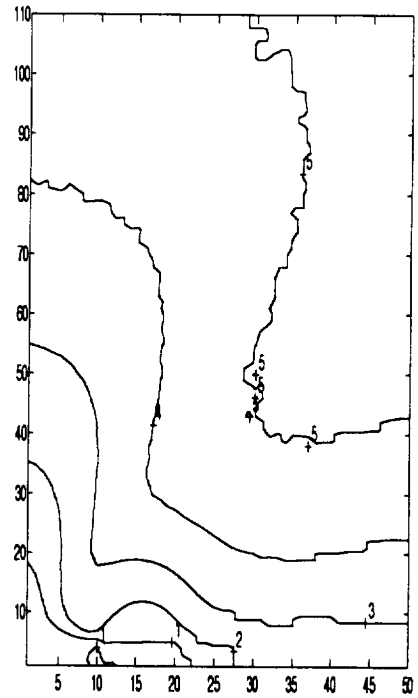

Figure 3: Mach contours in xy plane for $L/d = 3.0$

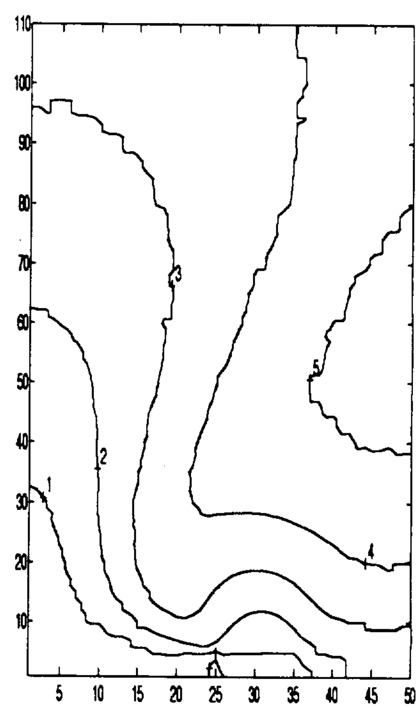

Figure 4: Mach contours in xy plane for $L/d = 6.0$

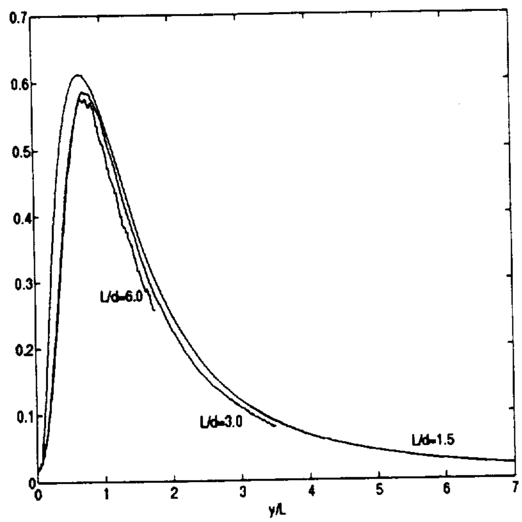

Figure 5: Normalized density scaled by $(L/d)^2$ along the secondary jet axis.

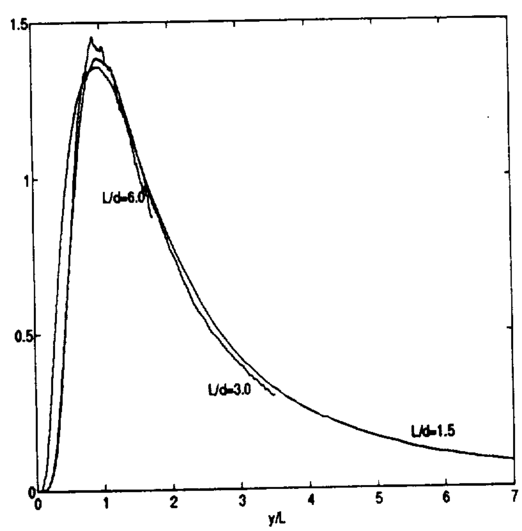

Figure 6: Normalized dynamic pressure scaled by $(L/d)^2$ along the secondary jet axis.

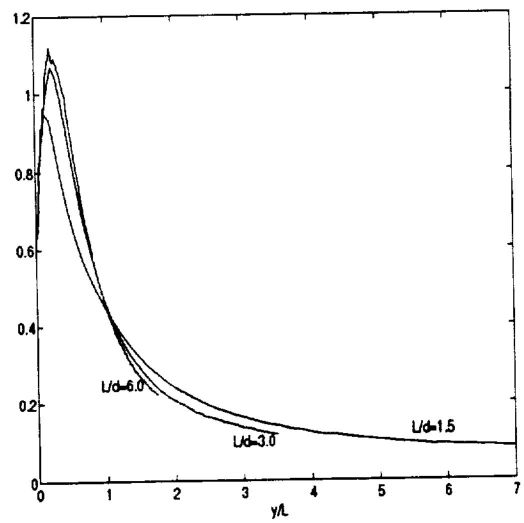

Figure 7: Normalized translational temperature scaled by $(L/d)^2$ along the secondary jet axis.

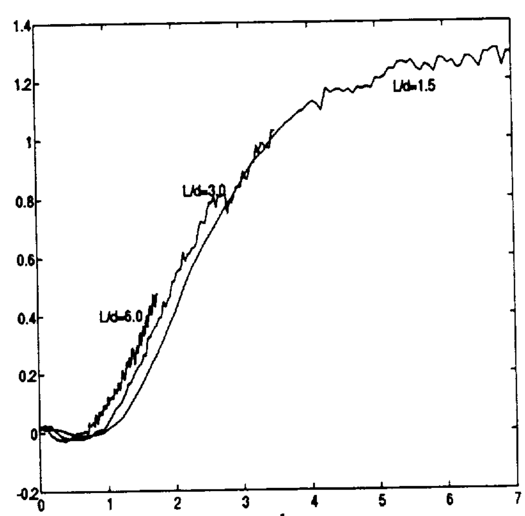

Figure 8: Relative difference in density between the dual jet plume and the undisturbed free jet along the primary jet axis.

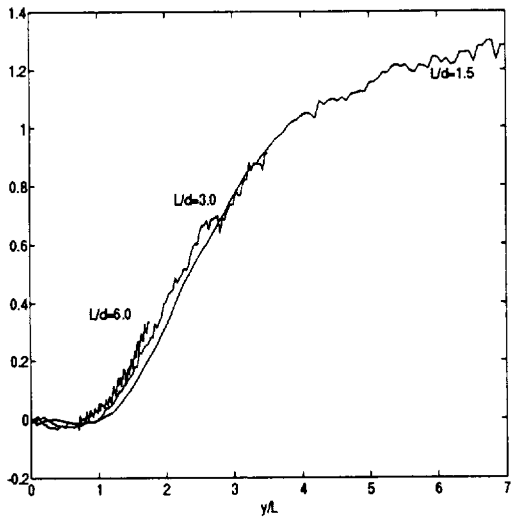

Figure 9: Relative difference in dynamic pressure between the dual jet plume and the undisturbed free jet along the primary jet axis.

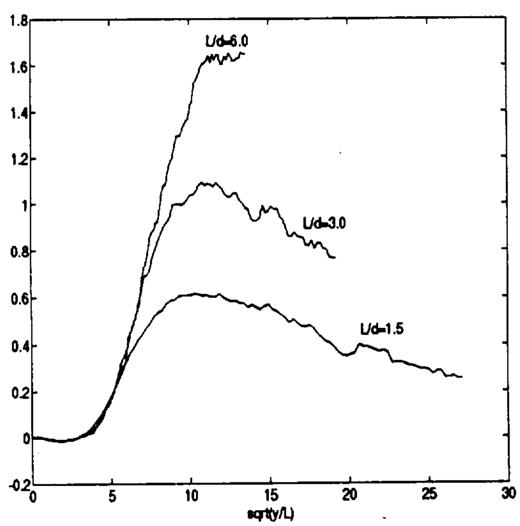

Figure 10: Relative difference in translational temperature between the dual jet plume and the undisturbed free jet along the primary jet axis.

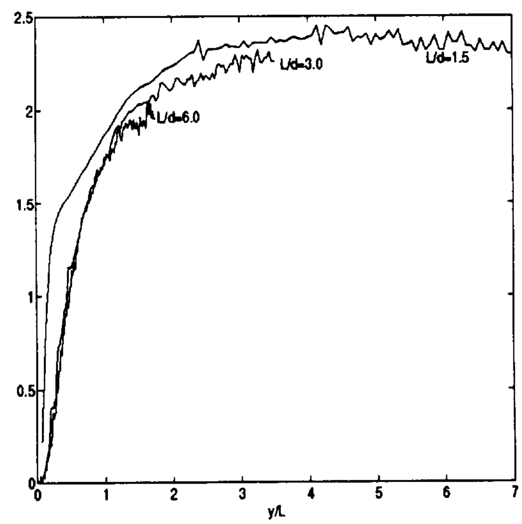

Figure 11: Ratio of dynamic pressure along secondary jet axis and in the undisturbed free jet at the same location.